An Update on the Google's Quantum Computing Initiative

(Bringing Tiny Iron to a Big Iron Fest)

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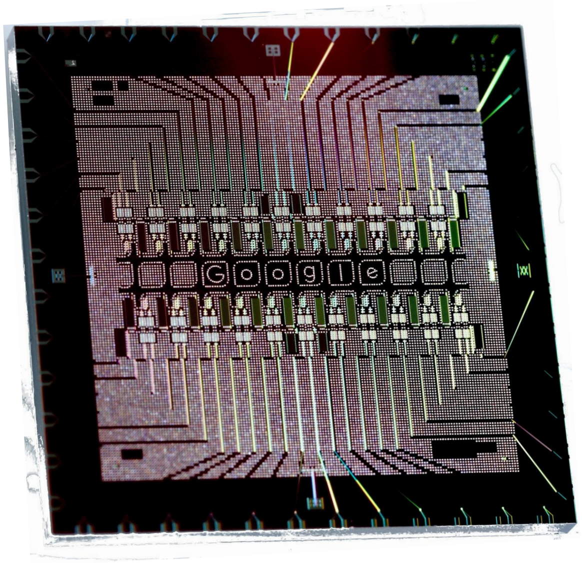
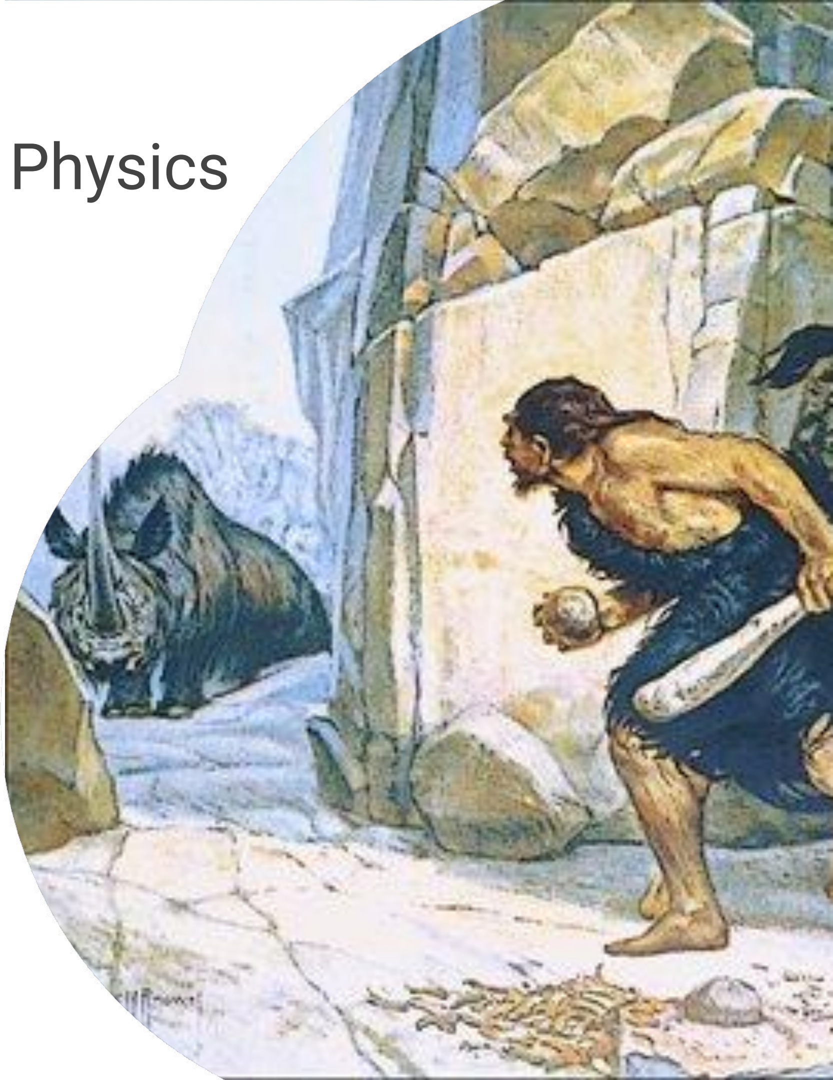


Our Brains are Wired for Newtonian Physics

Brains that recognize and anticipate behaviors of Heat, Light, Momentum, Gravity, etc. have an Evolutionary Advantage.

Quantum phenomena contradict our intuition.



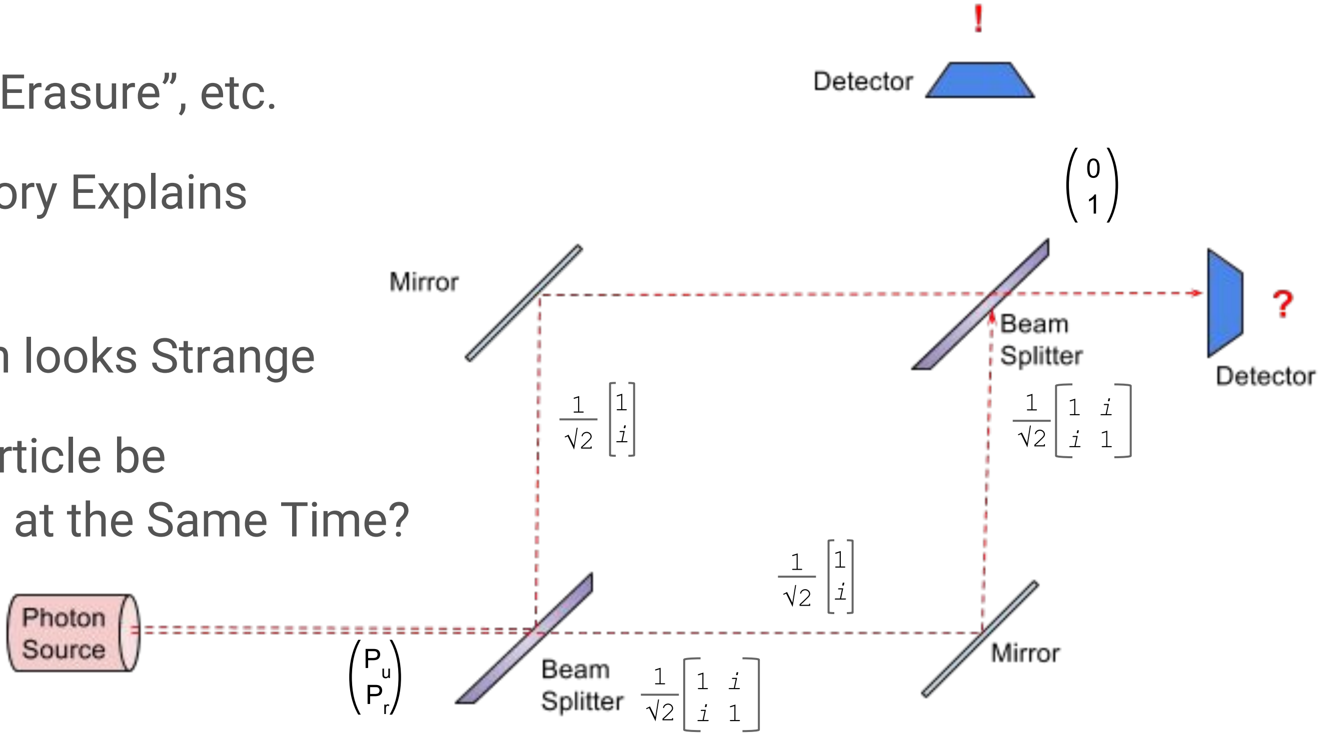
Quantum Phenomena Contradict Intuition

Interference, “Erasure”, etc.

Quantum Theory Explains Cleanly…

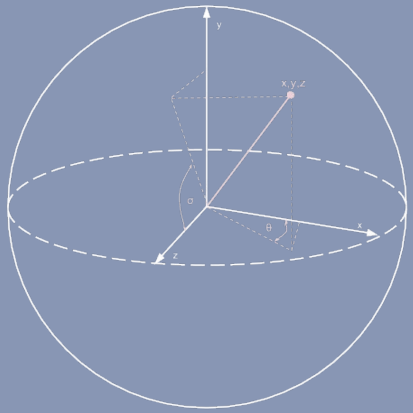
…but the Math looks Strange

How can a Particle be
On Two Paths at the Same Time?



Quantum Data

$$|0\rangle + |1\rangle$$



Quantum Data

$$(\,|0\rangle+|1\rangle\,)^2=|00\rangle+|01\rangle+|10\rangle+|11\rangle$$

Really Big Data

$$(|0\rangle + |1\rangle)^n$$

n=50: supercomputer

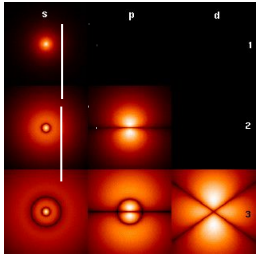
n=300: more states than atoms in universe

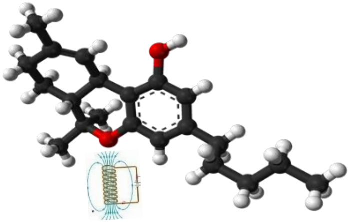
Macroscopic QM Enables New Physics

Control of single quantum systems, to quantum computers

1 nm

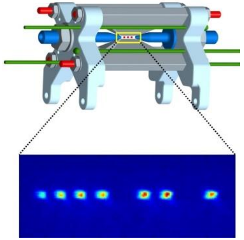
H atom wavefunctions:

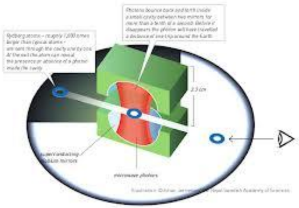


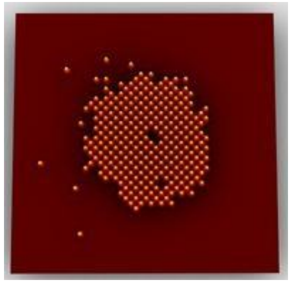


Problem:
Light is 1000x larger

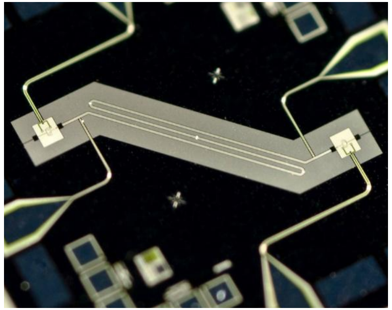
1 μm

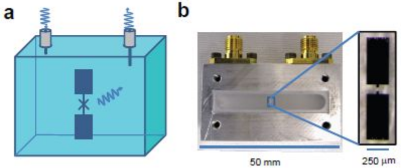






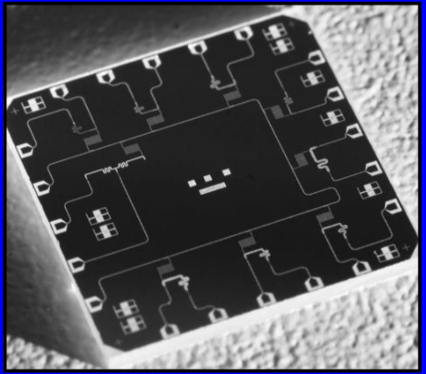
1 mm





Large “atom” has room for complex control

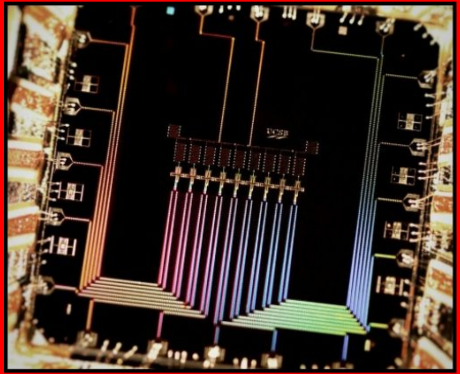
Quantum Chips at Google



Fluxmon

Flux qubit with tunable coupling

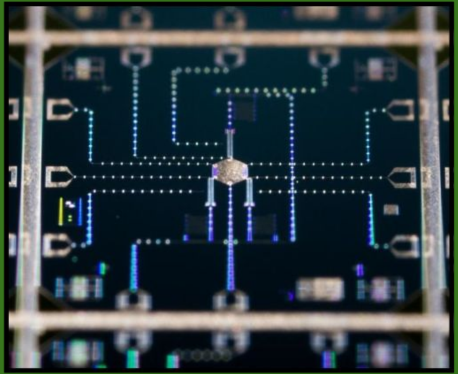
Good for optimization problems



Xmon

X-shaped transmon qubit

Good for building a digital, gate-based quantum computer (requires error correction)



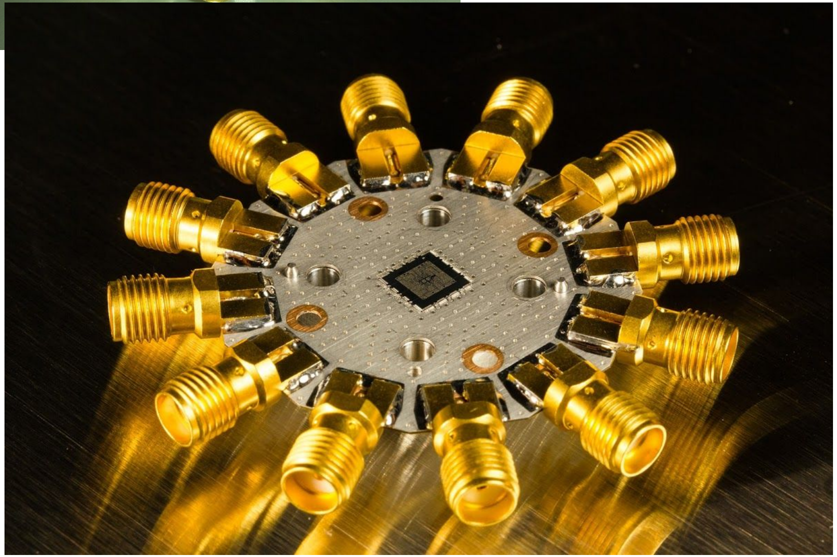
Gmon

Transmon qubit with tunable nearest-neighbor coupling

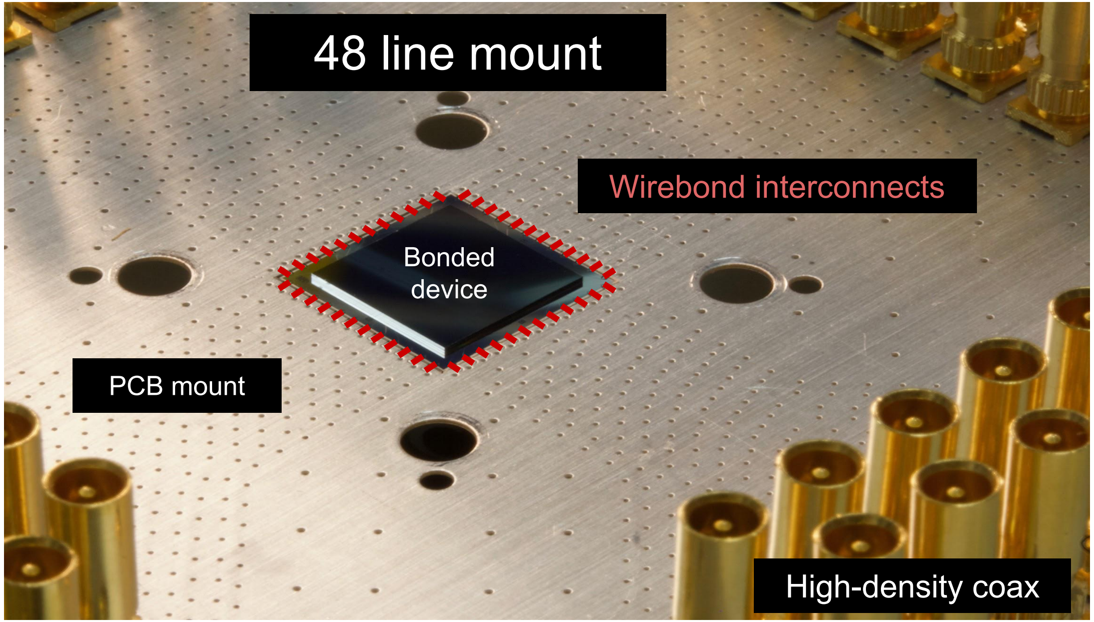
Good for simulation problems

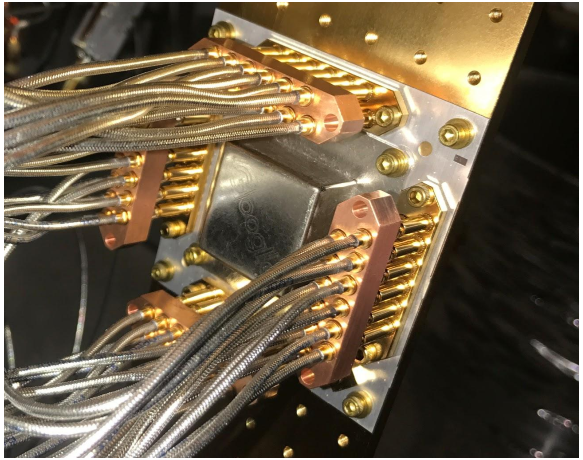
Chip mount: PCB

- Printed circuit board chipmount
- Uses superconducting aluminum
- Wire bonding is easy with automatic wire bonder
- Easy to leave space for differing thermal expansion
- Eventually abandon SMA connectors for something smaller

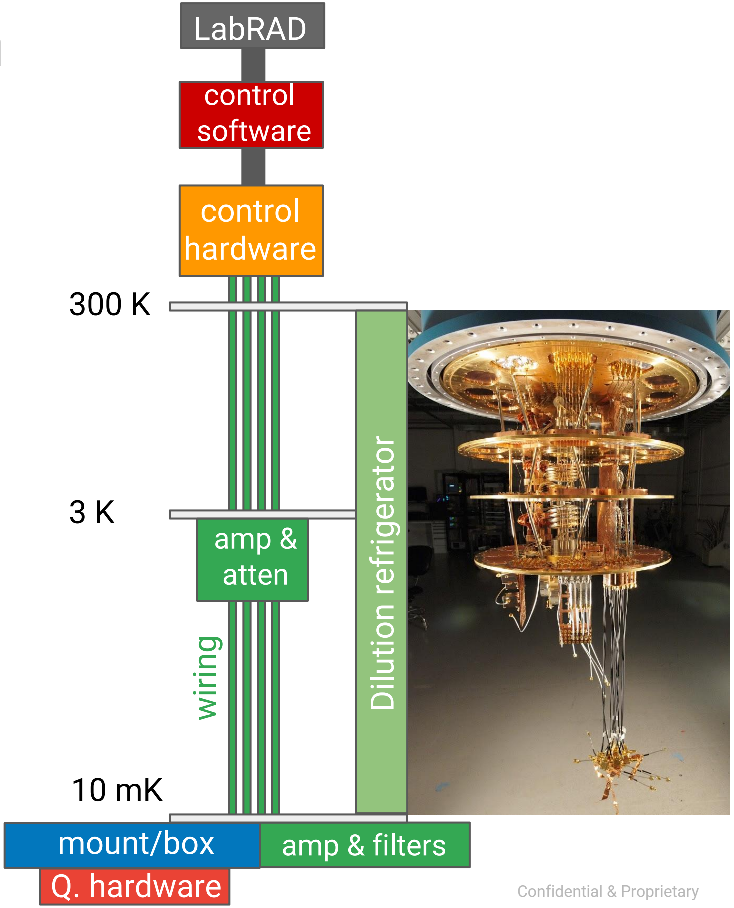


Scaling to O(50) Qubits





Quantum Computer System Design



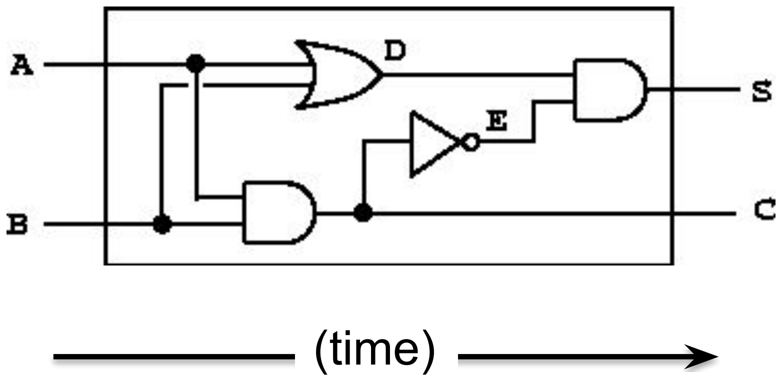
Logic Built from Universal Gates

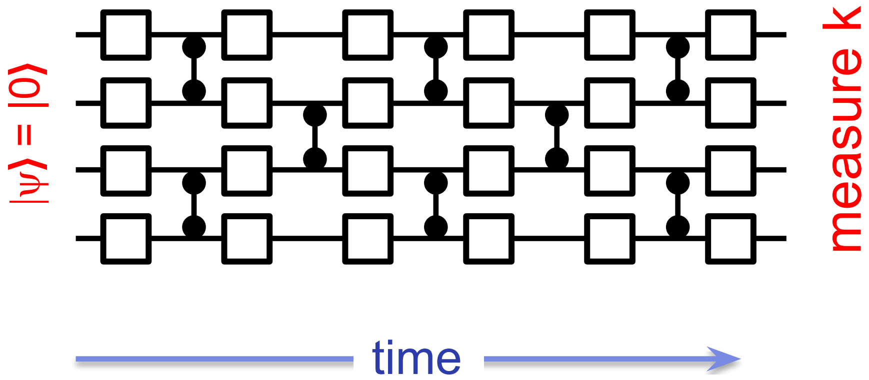
Classical circuit:

1 bit NOT
2 bit AND
Wiring fan-out

Quantum circuit:

1 qubit rotation
2 qubit CNOT
No copy

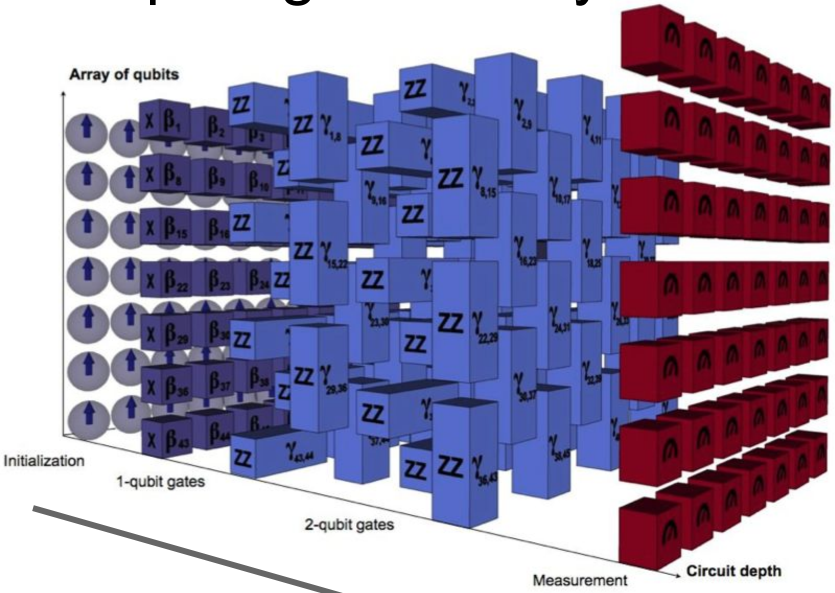




Space-Time Volume of a Quantum Gate Computation

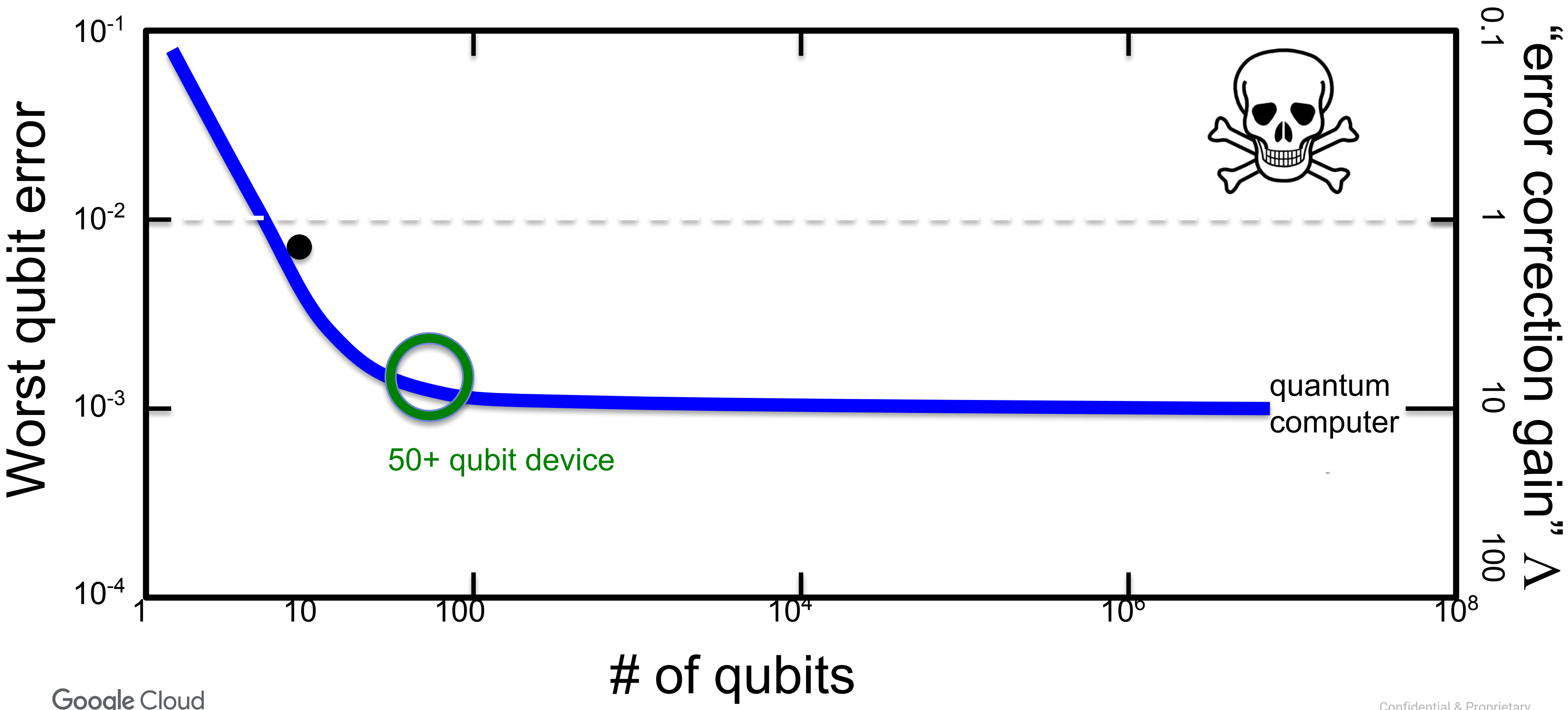
Uncorrected Gate "Circuits" Limited by Fidelity of Operations and Decoherence Times

2 qubit gate fidelity = 99.5%



Gate Depth

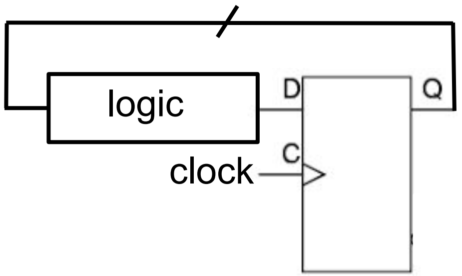
Systems: Quantity and Quality



The Clocked Logic Analogy

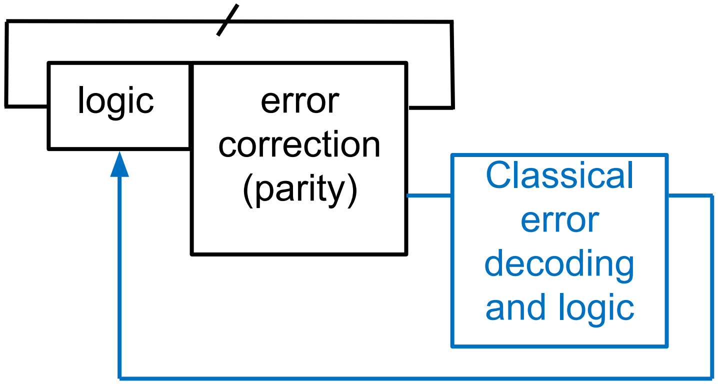
<u>Classical system:</u>

D flip-flop aligns timing to clock



<u>Quantum system:</u>

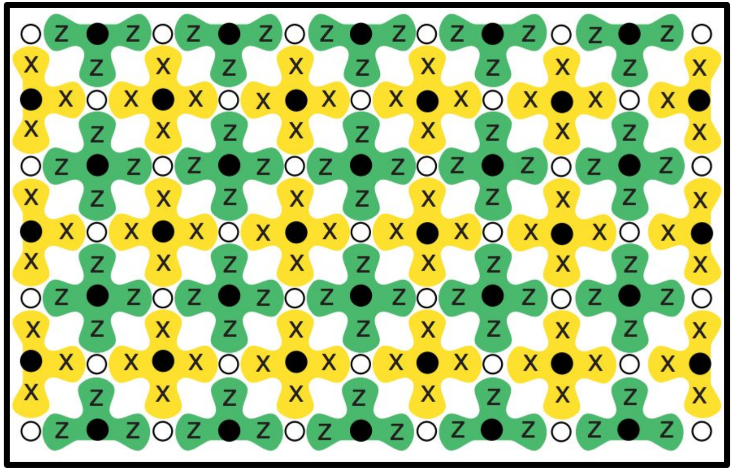
Error correction aligns amplitude and phase each round, makes “quantum flip-flop”



Need 1000 qubits + 0.1% errors

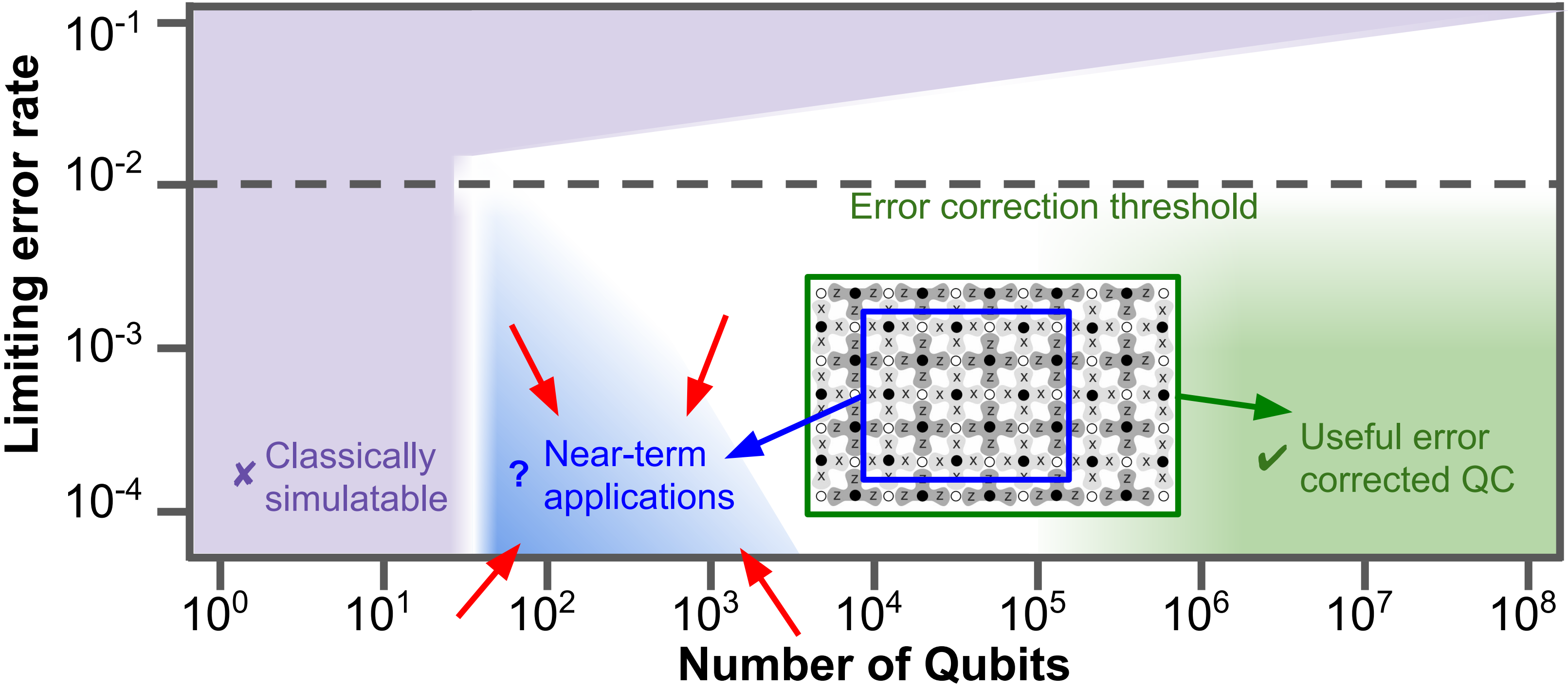
Towards a Universal Fault-Tolerant QC

- Qubit error rates ~10^{-2}-10^{-3} per operation
- Universal QC requires ~10^{-10}
- Error correction:
  - Low error logical qubit made with multiple physical qubits
- Surface code error correction:
  - 2D array of qubits (n.n. coupling)
  - Modest error rates (1% threshold, 0.1% target)
  - Useful at 10^6 physical qubits



Need error correction long term.
Can we do something sooner?

When is a Quantum Computer Useful?



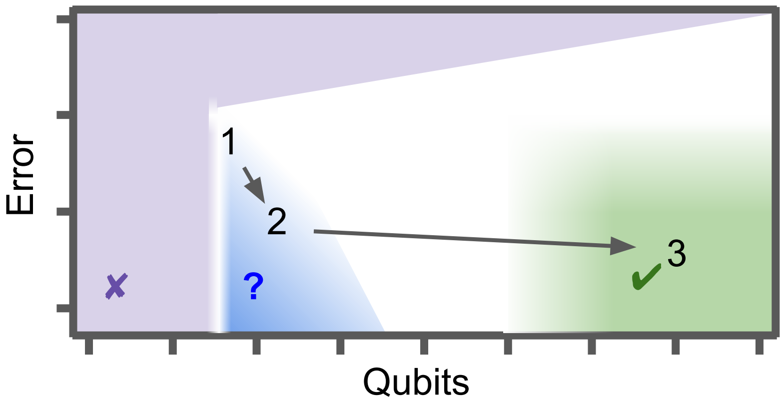
Idea: use modest 2D array of qubits, explore beyond classical sims

Google Quantum Computing Milestones

Milestones:

1. Build a quantum processor that can outperform a classical supercomputer at *something*
2. Find an near-term application that can be solved with QC
3. Build fault-tolerant QC

3 is harder than 2, is harder than 1

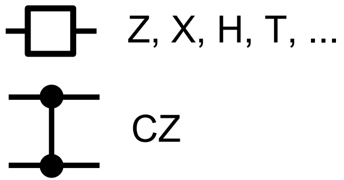


Hardware strategy: start with 1 (“Quantum Supremacy”)

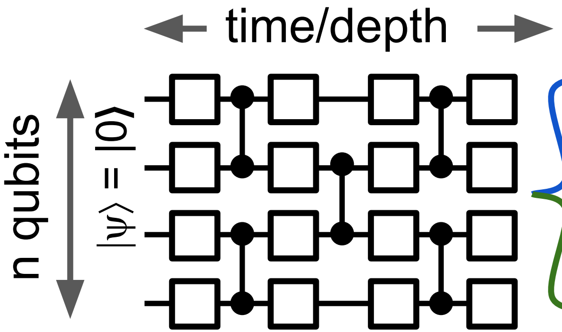
Meas. System Performance: Random Circuits

- Validate gate performance
  - Randomized benchmarking: generate circuit, measure fidelity, repeat
- How to validate full system performance?
  - Same idea: pick random circuit, measure fidelity, repeat

Gates



1. Pick circuit



2. Run circuit

Classical Computer → Compute ideal $|\psi\rangle$

Quantum Computer → Measure output state **k** (bitstring, 2^n possible)
Repeat sampling x100,000

3. Measure fidelity

Probability of meas. **k**
$p(\mathbf{k}) = |\langle \mathbf{k}|\psi\rangle|^2$

Fidelity
$F \propto \langle \ln[p(\mathbf{k})2^n] \rangle$

4. Repeat, average

circuits

Measure fidelity over whole system

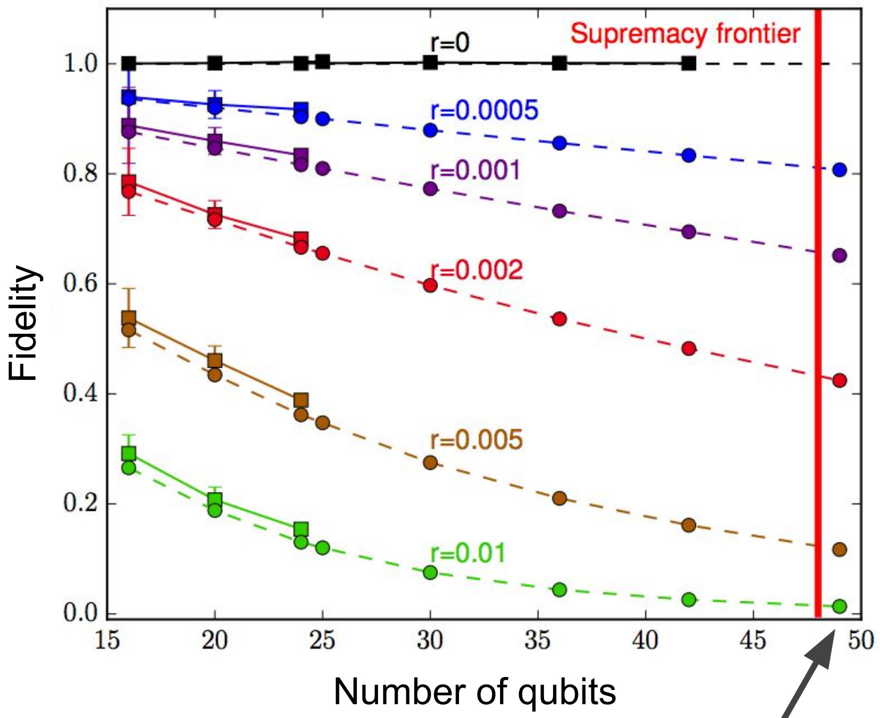
“Quantum Supremacy”?

Below 50 qubits, circuit depth 40

- Supercomputer can simulate all, can measure fidelity

Above 50 qubits, circuit depth 40

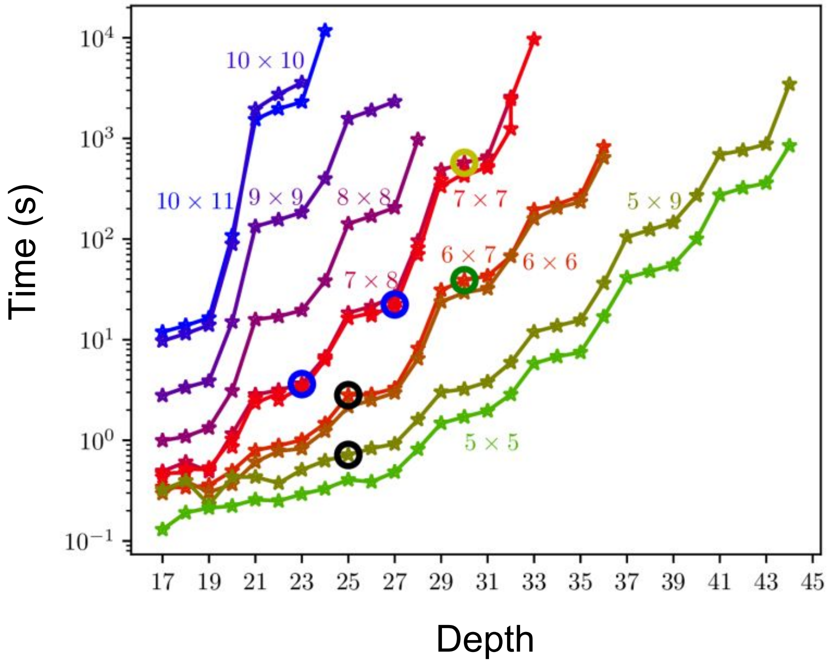
- Supercomputer can’t simulate, can *only* extrapolate fidelity
- Quantum system computing well-defined problem that supercomputer can’t: “Quantum Supremacy”



Full system performance needed: quality + quantity

A note on circuit depth

- Circuit depth as important as qubit number
- 110 qubits simulatable at depth 23
- 45 qubits just as hard at depth 44

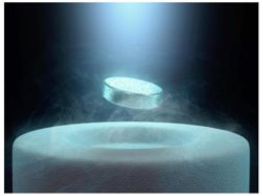


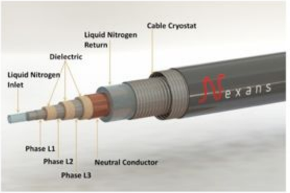
Both qubit number, depth needed to be classically hard

Sergio Boixo, et al.
Figure 13: arXiv 1608.00263
Figure 1: arXiv 1712.05384

Feynman’s Killer App: Simulation of Quantum Systems

30% of cycles on DOE computers spent on: quantum simulation for materials, drug design, solar cells, industrial catalysts, energy

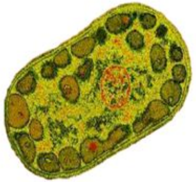




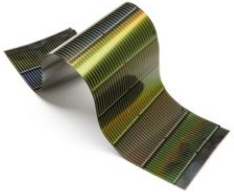
$$H = -t \sum_{\langle pq \rangle} \sum_{\sigma} (a^{\dagger}_{p,\sigma} a_{q,\sigma} + c.c.) + U \sum_{p} a^{\dagger}_{p,\uparrow} a_{p,\uparrow} a^{\dagger}_{p,\downarrow} a_{p,\downarrow}$$

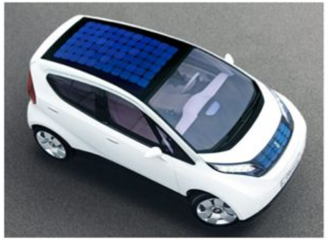
The Fermi Hubbard model: the key to high temperature superconductivity

Haber process: 2% of world energy
$N_2 + 3\ H_2 \rightarrow 2\ NH$: 500°C, 20 Mpa

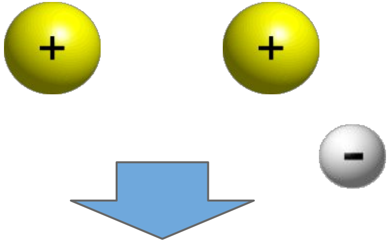


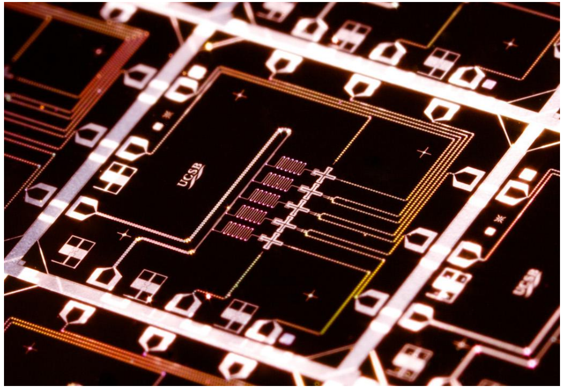
Simulations of energy transport:
the key to economic and efficient solar

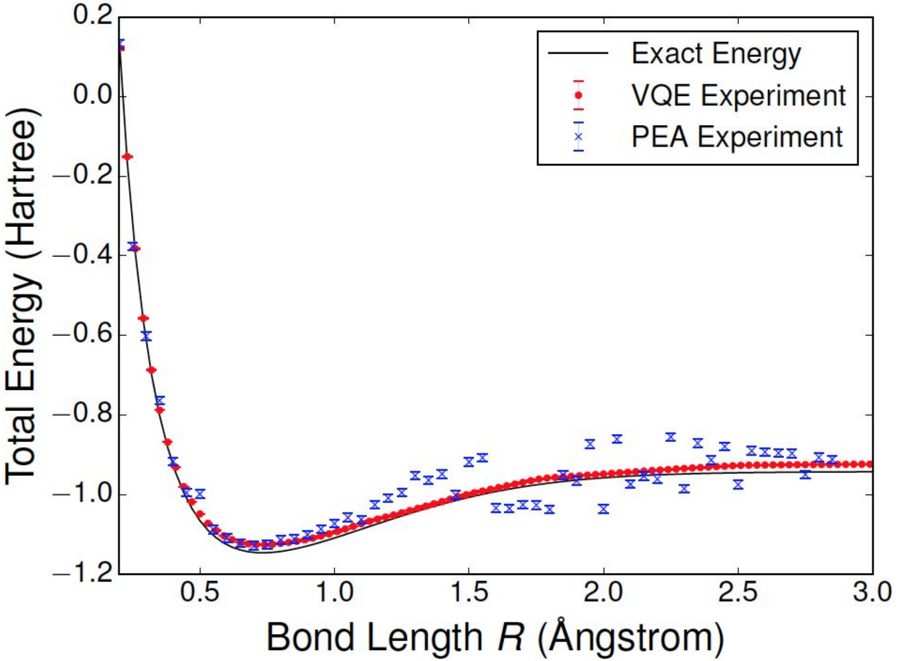




Hydrogen Quantum Simulation



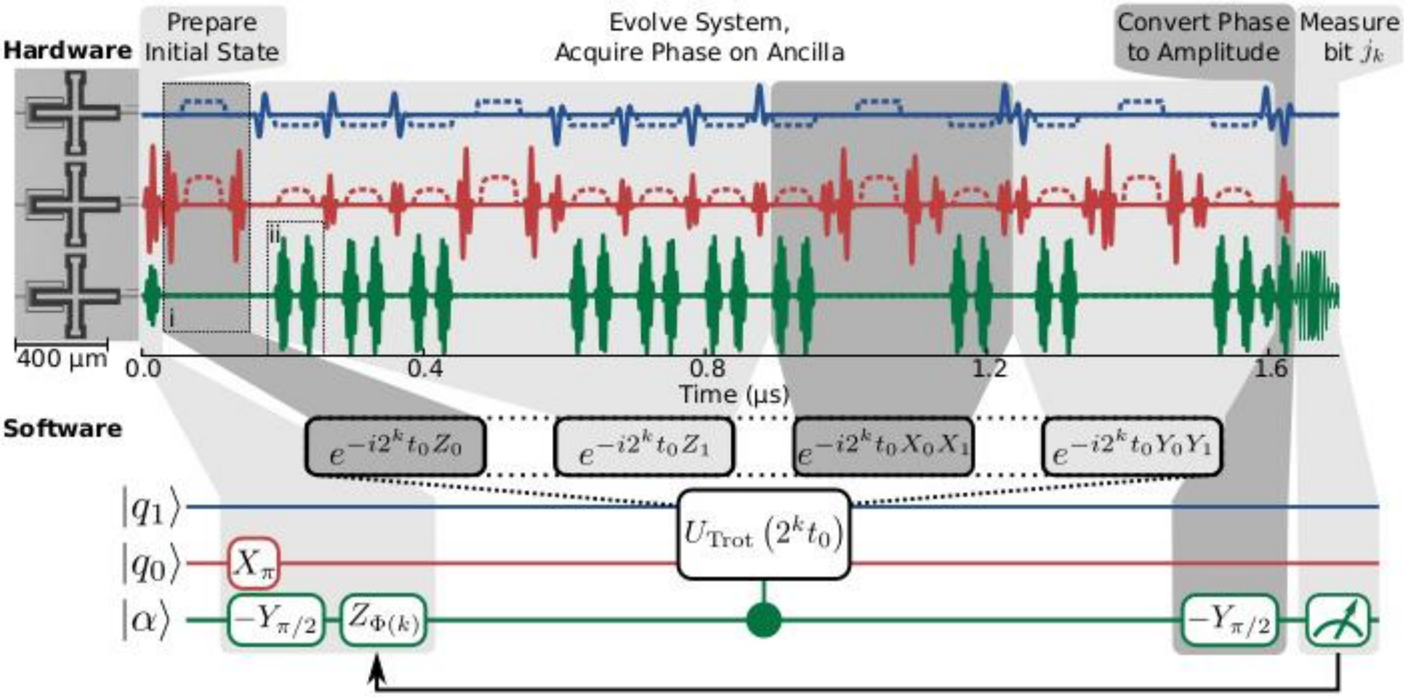




Predicted dissociation energy for first time !

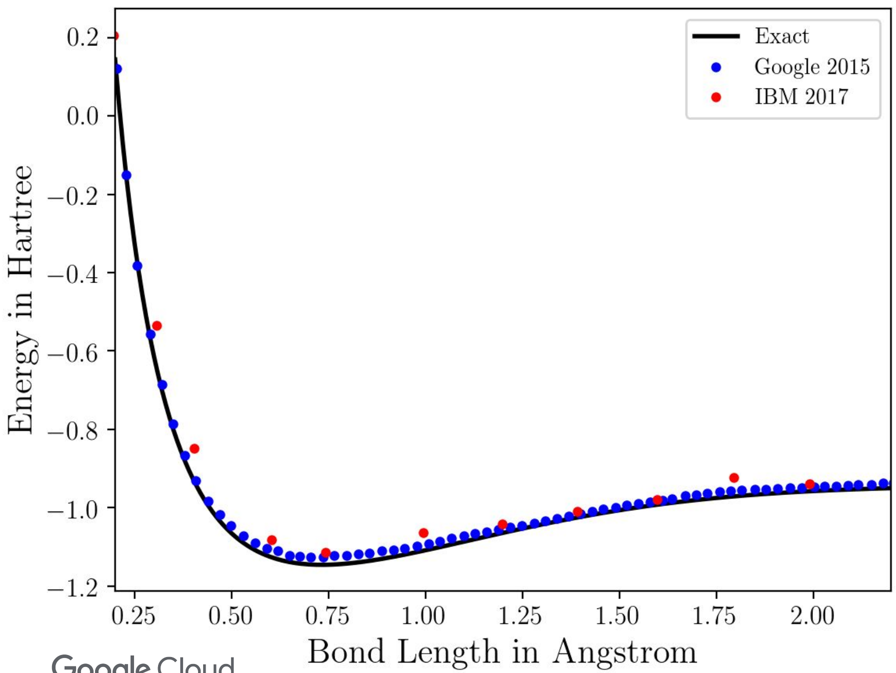
P. O'Malley, R. Babbush *et al.* arXiv preprint: 1512.06860

Execution of a Quantum Simulation

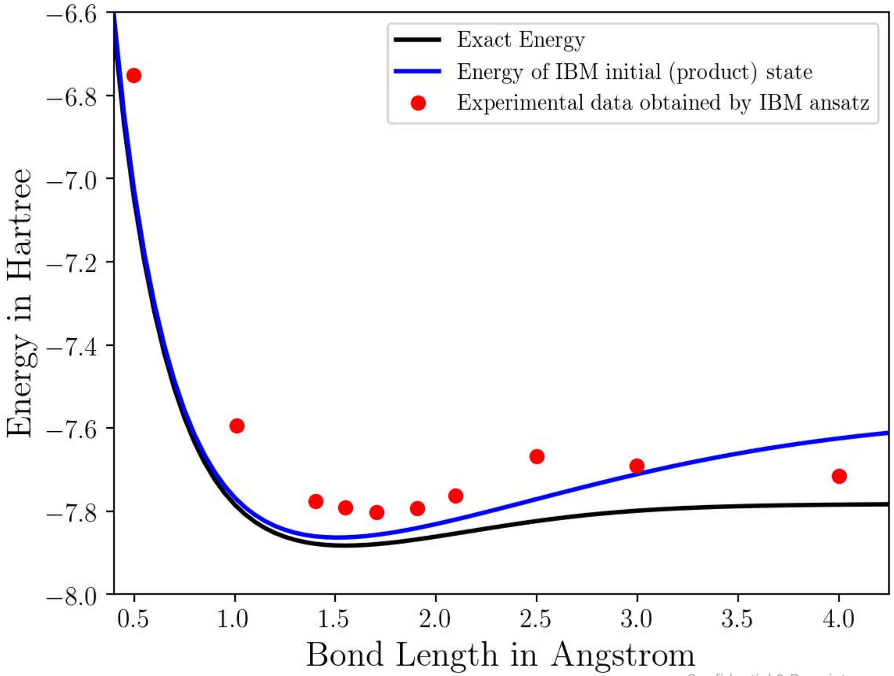


Quality in Quantum Chemistry Experiments

H_2 Molecule

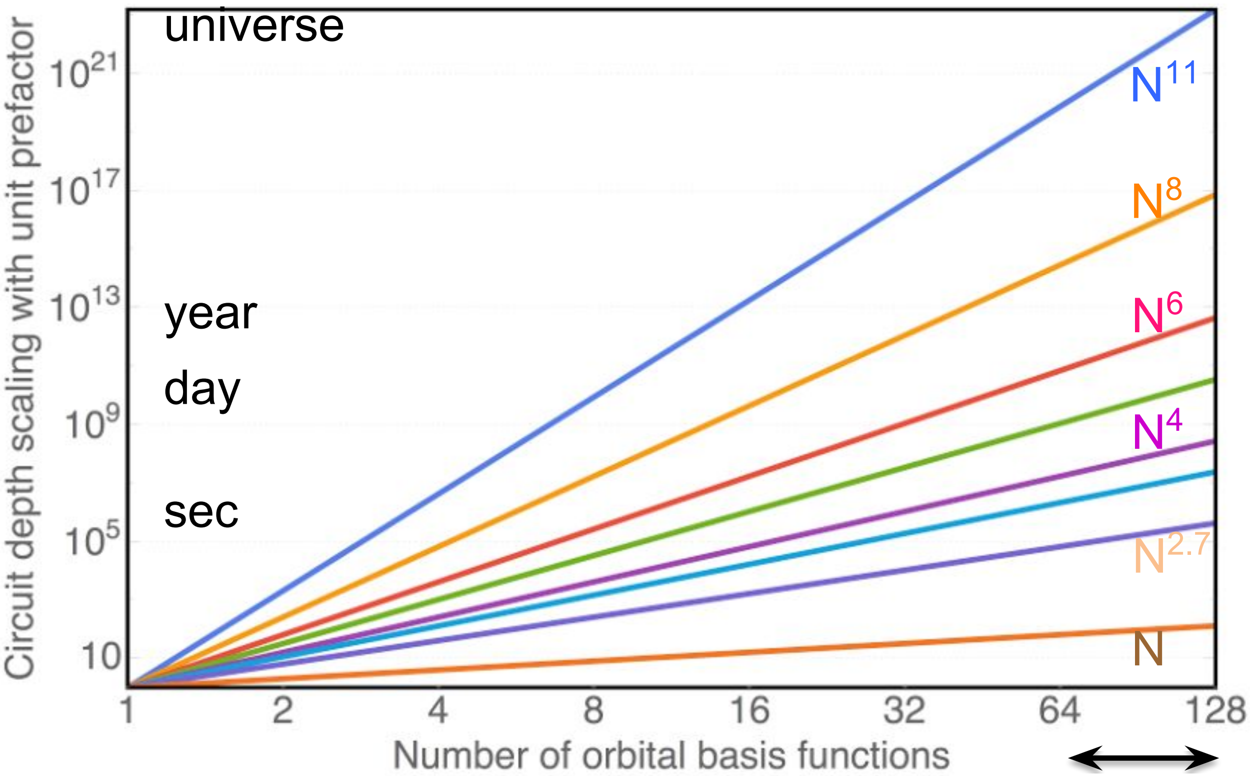


LiH Molecule



Huge Progress in Algorithms (Quantum Chemistry)

Year	Reference	Total Depth
1985	**Feynman**	**(proposal)**
2005	Aspuru-Guzik [1]	$\mathcal{O}(\text{poly}(N))$
2010	Whitfield [2]	$\mathcal{O}(\text{poly}(N))$
2012	Seeley [3]	$\mathcal{O}(\text{poly}(N))$
2013	Perruzzo [4]	$\mathcal{O}(\text{poly}(N))$
2013	Toloui [5]	$\mathcal{O}(\text{poly}(N))$
2013	Wecker [6]	$\mathcal{O}(N^{11})$
2014	Hastings [7]	$\mathcal{O}(N^{8})$
2014	Poulin [8]	$\sim N^6$
2014	McClean [9]	$\sim N^6$
2014	Babbush [10]	$\sim N^5$
2015	Babbush [11]	$\tilde{\mathcal{O}}(N^5)$
2015	Babbush [12]	$\tilde{\mathcal{O}}(\eta^2 N^3)$
2015	Wecker [13]	$\mathcal{O}(N^4)$
2016	McClean [14]	$\mathcal{O}(\eta^2 N^2)$
2017	Babbush [15]	$\mathcal{O}(\eta^{1.83} N^{1.67})$
2017	Babbush [15]	$\tilde{\mathcal{O}}(N^{2.67})$
2017	Babbush [15]	$\mathcal{O}(N)$



Exact: 100 logical qubits (error corrected)

Approximate: 100 physical qubits (?)

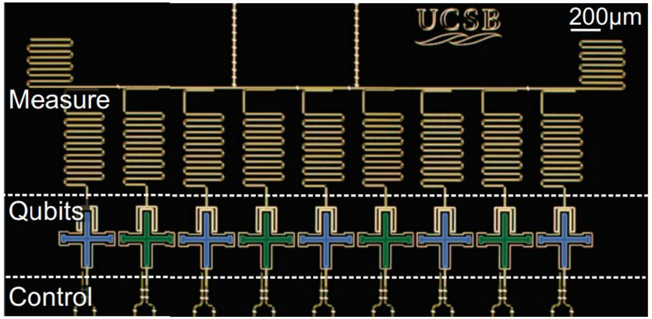
9 Qubit: Good performance, Limited Planar

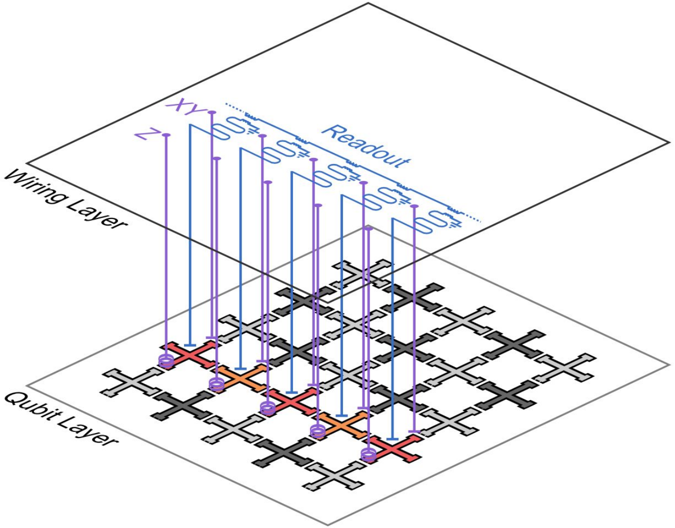
9 qubit device has good performance

- Err_{CZ} down to 0.6%
- Err_{SQ} < 0.1%
- Err_{RO} = 1%

Limited to 1D connectivity (planar geometry)

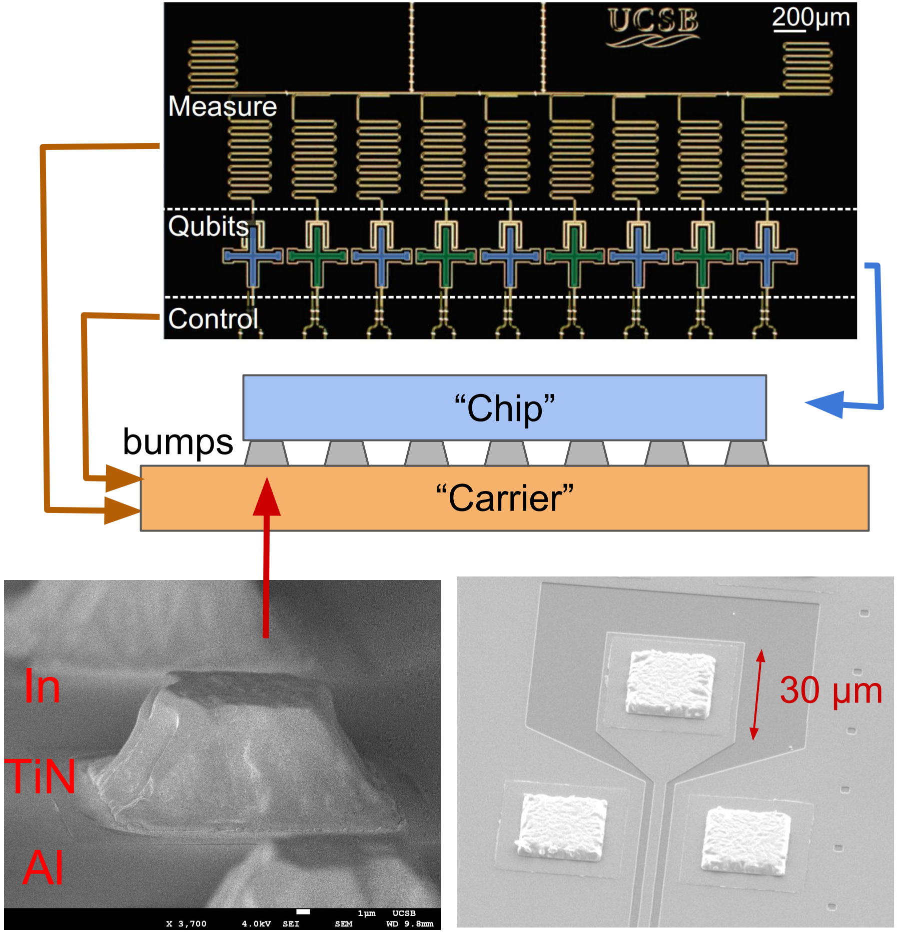
2D scale up strategy: move qubits, control to different planes



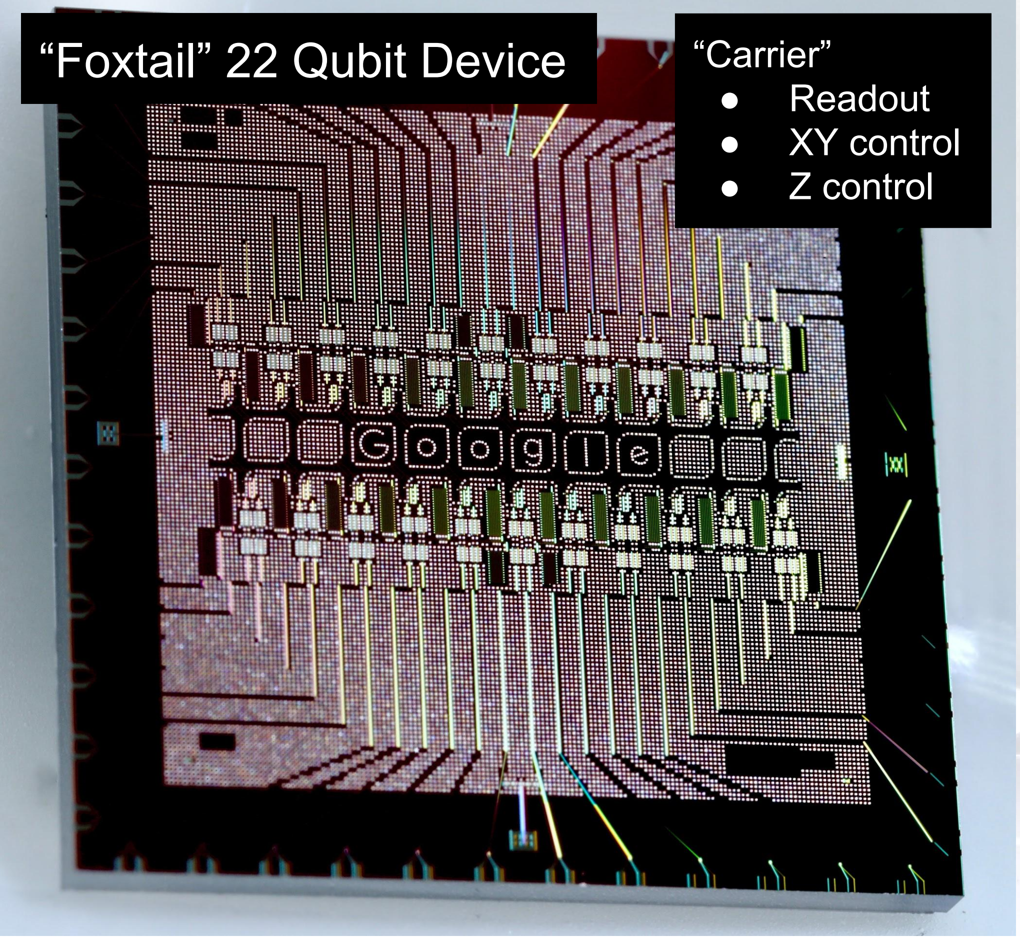


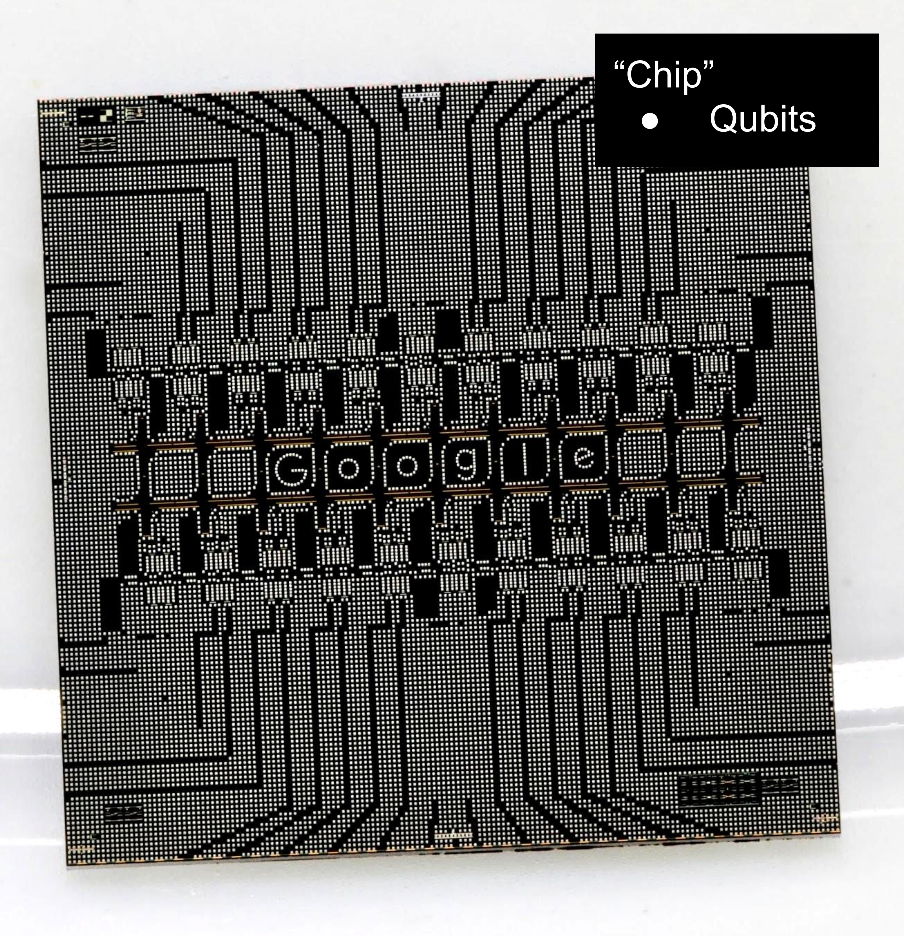
Bump bond architecture

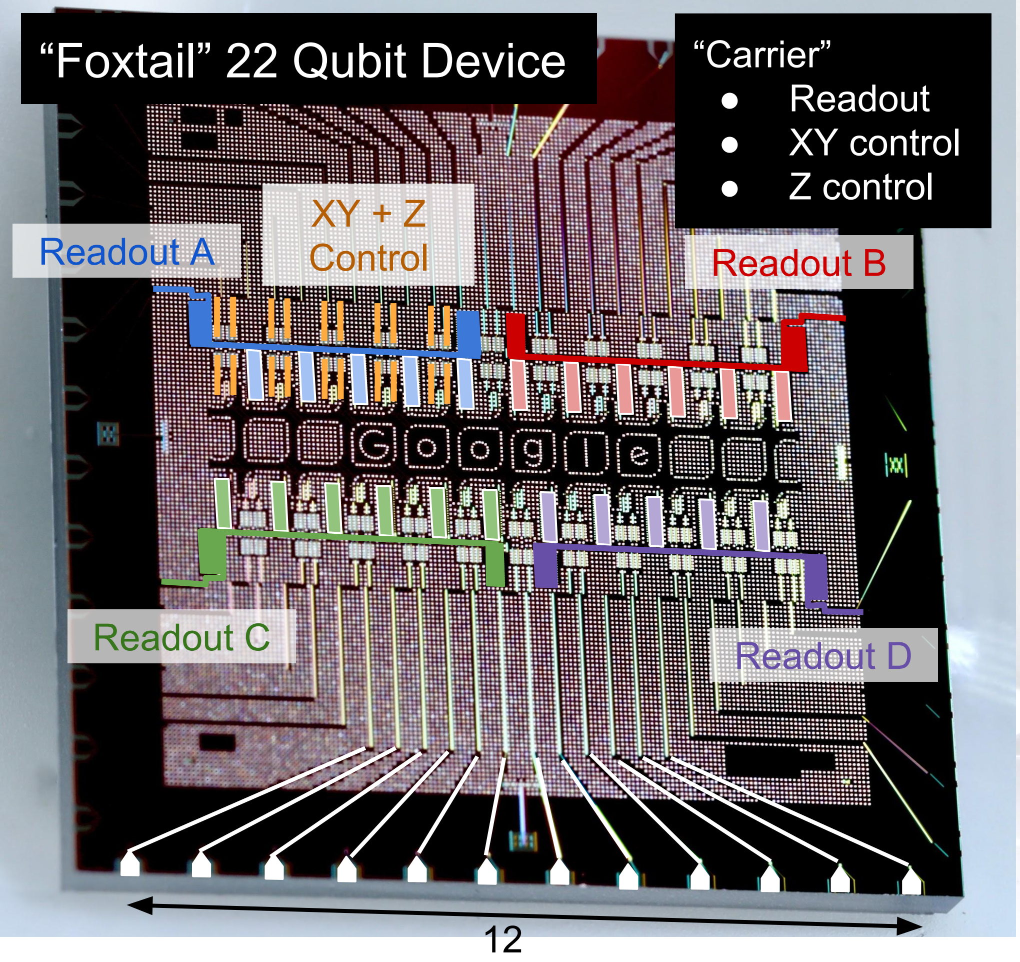
- Bond together two separate chips
    - Qubits → “Chip”
    - Control → “Carrier”
- Superconducting interconnect
- Use lossless vacuum as dielectric

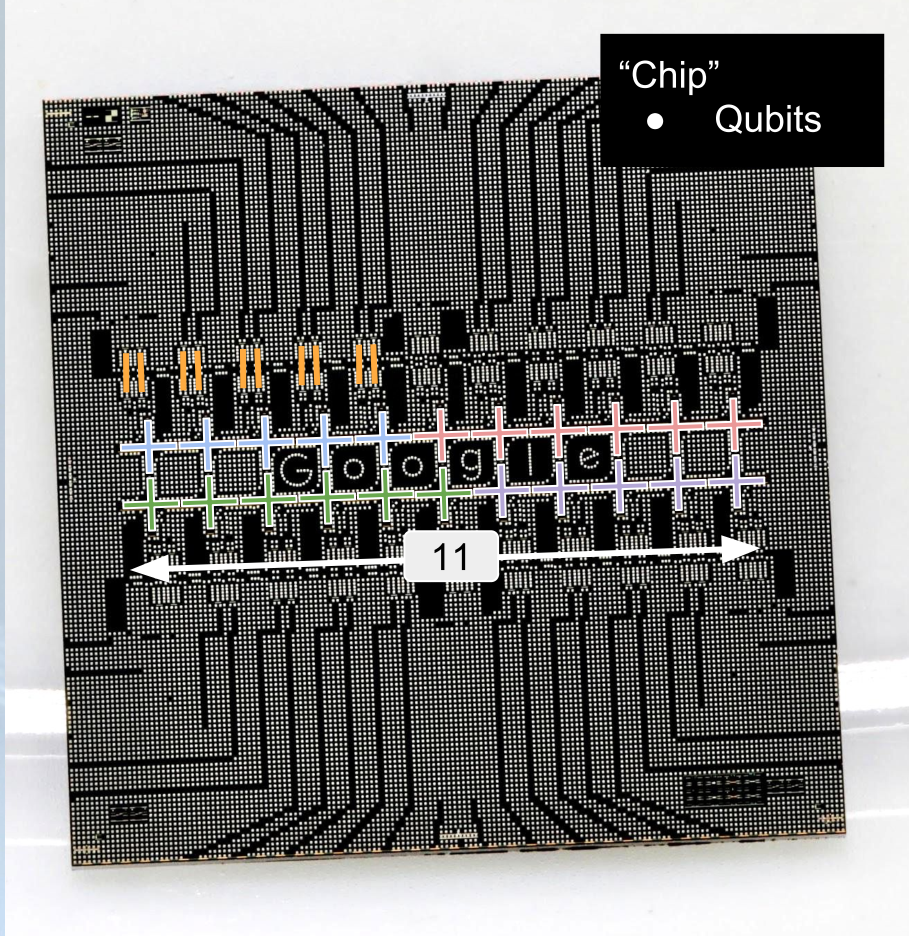


“Foxtail” 22 Qubit Device









- 2x11 grid
- 48 waveguides
- 4 readout lines
- 5-6 qubits per cell

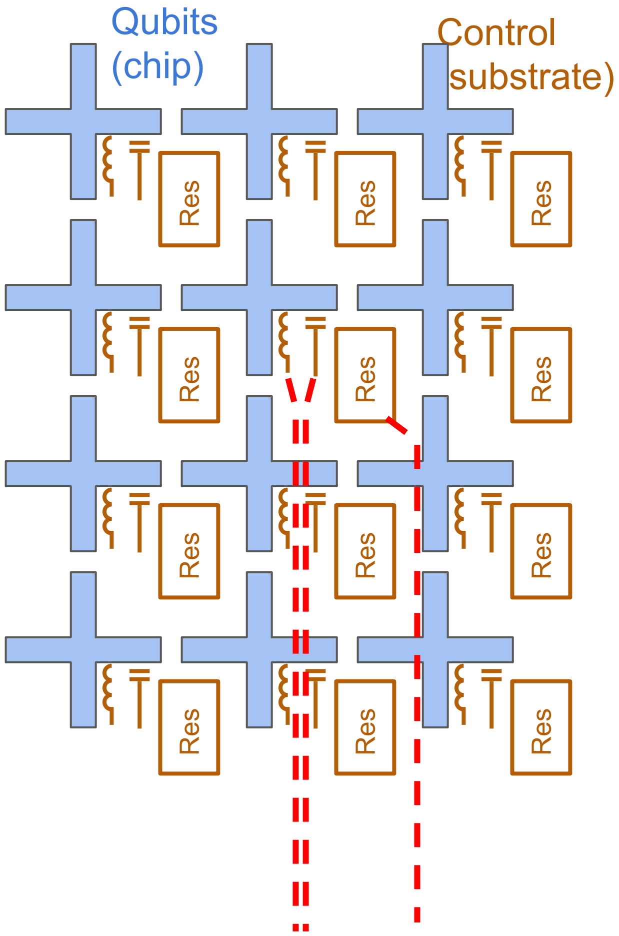
How to scale to 2D

Design must be “tileable” (control fits in qubit footprint)

- Readout resonator
- XY coupler
- SQUID coupler

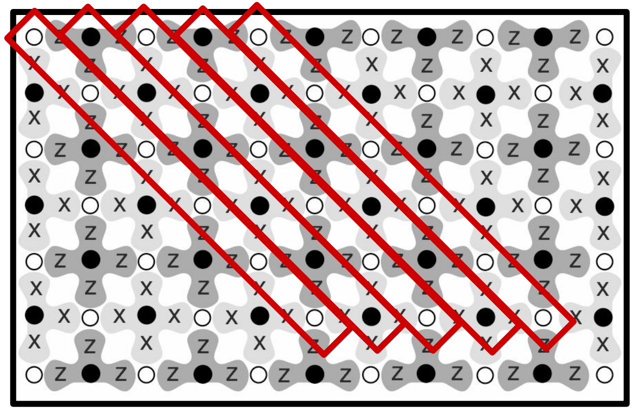
Need to shield qubits from interior wire routing

- Small coupling to 50Ω line will decohere qubit

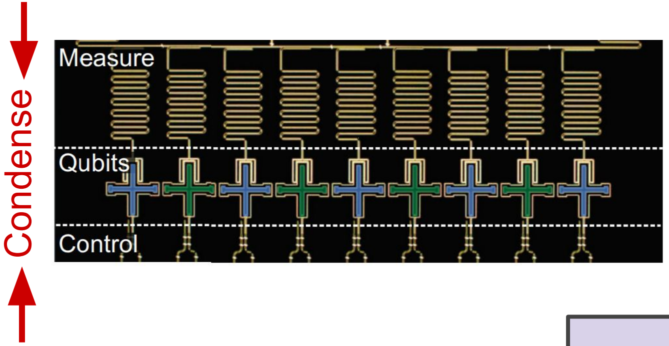


2D unit cell

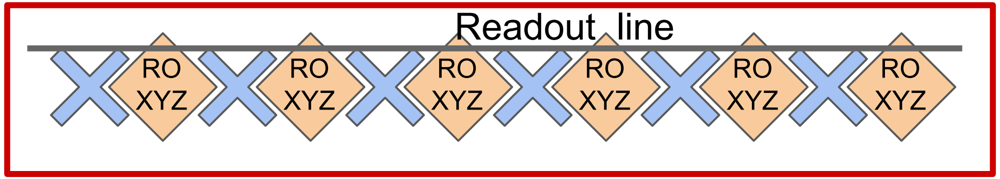
- Diagonal for surface code: all “measure” qubits on same line
- Condense footprint across 2 chips
- Introduce shielded wiring between qubits
- Tile unit cell for 2D array



Unit cell: Condensed, diagonal linear chain

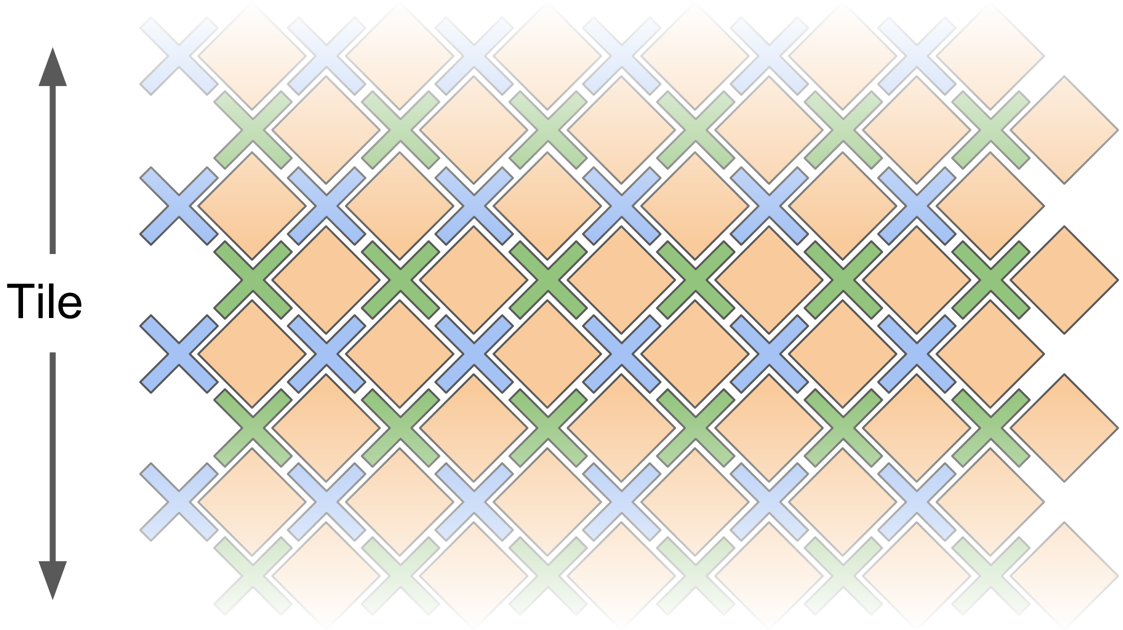


rotate



Unit cell designed for surface code

“Bristlecone” Architecture

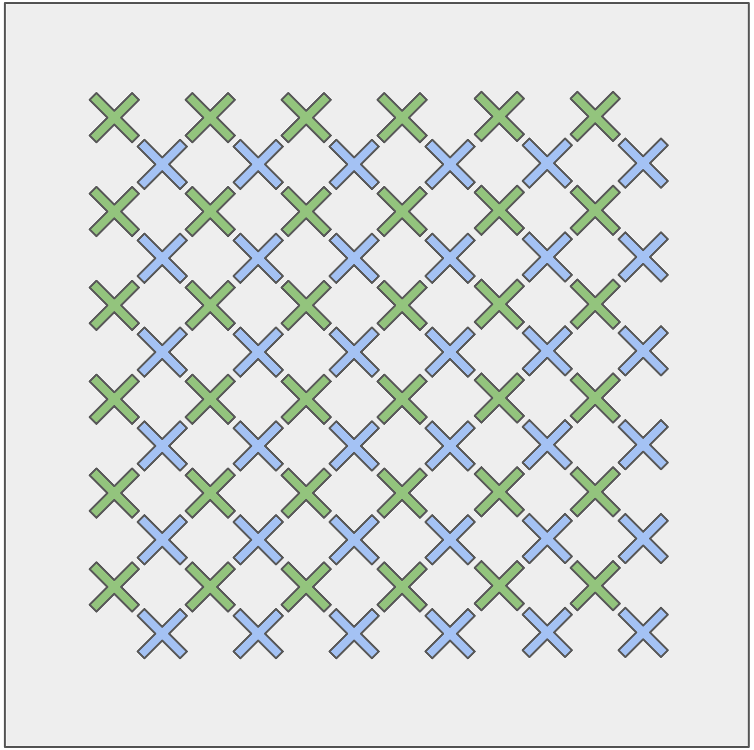


Bristlecone

Tile for a 2D grid of n.n. coupled qubits
Bonus: Looks like a pine cone!

"Bristlecone" Schematic

Bristlecone

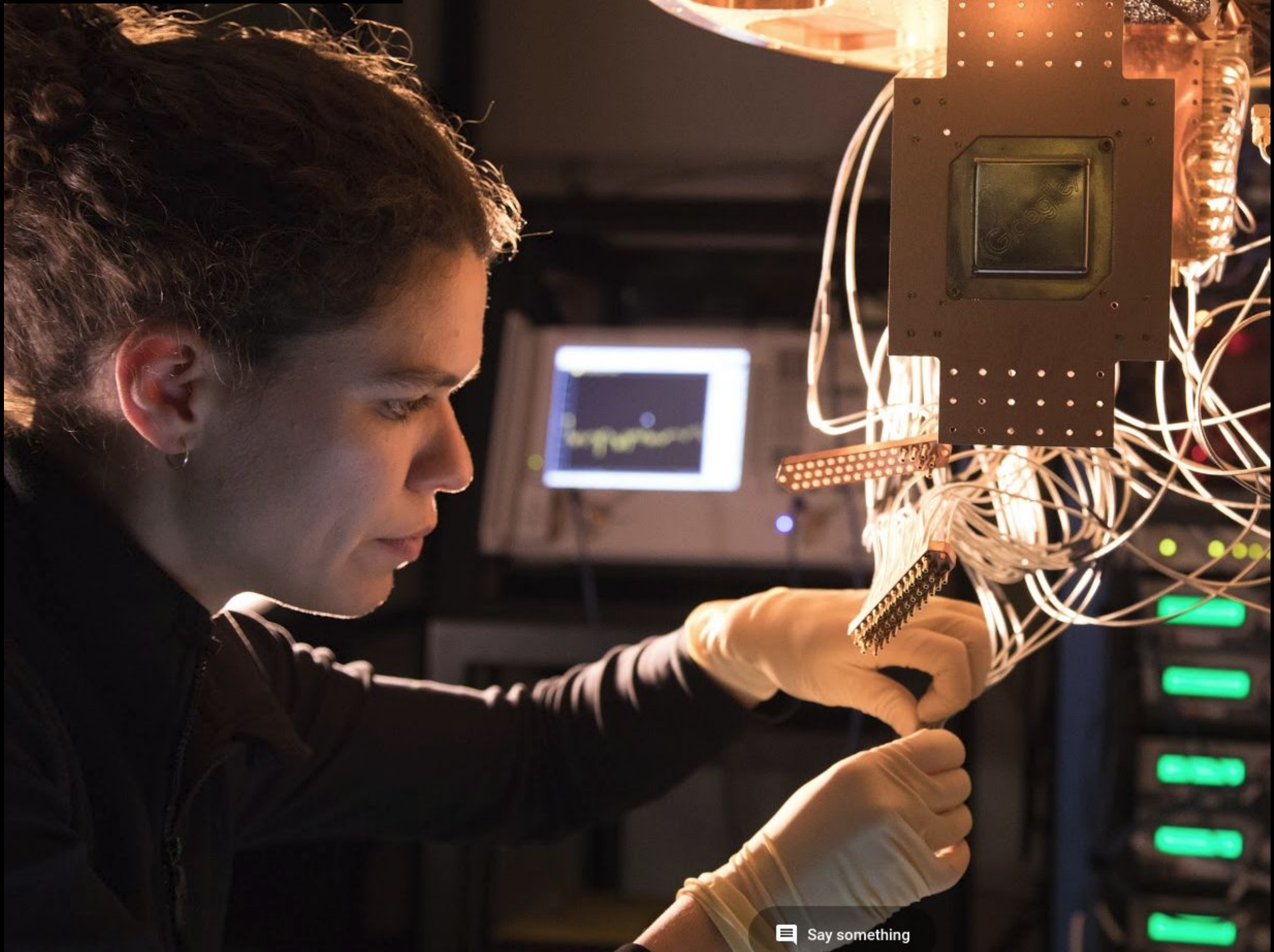


12 unit cells of 6 qubits = 72 qubits

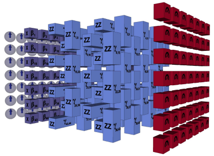
- Enough for "Quantum Supremacy"
- Enough for 1st, 2nd order Surface Code
- Starting point for near-term algorithms

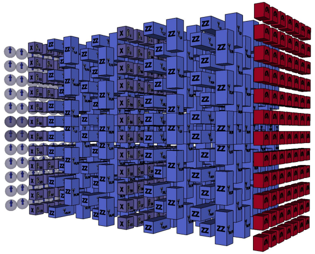
Photo: Erik Lucero

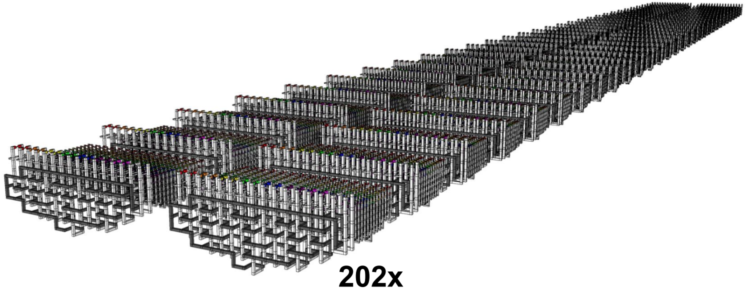
Bristlecone in test



Quantum Computer Timeline







201x

202x

Quantum supremacy

Beyond classical computing capability demonstrated for a select computational problem

Pre-error corrected quantum processors

Early application wins expected for

- Simulation of Quantum Systems
- Optimization
- Sampling
- Quantum Neural Network

Error corrected quantum computer

Growing list of quantum algorithms for wide variety of applications with proven speedups

- Unstructured Search
- Factoring
- Semi-definite Programming
- Solving Linear Systems
- ...

Google quantum hardware team

Thanks for Your Attention!